DEVELOPMENTAL WORK ON AN INFRARED DETECTOR

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THESIS

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Captain, United States Army

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the requirements for the degree of
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ABSTRACT

A new type I R detector was constructed, employing a short circuited thermocouple to generate a magnetic field to deflect an electron beam onto an indicator. Thermocouple parameters and the magnetic deflection of the electron beam by a coil of wire, a loop of wire, and an internally mounted thermocouple loop were determined. Feasibility of such an instrument is established conditionally upon the construction of an electron gun with a well focused electron beam.

This thesis was written at the United States Naval Postgraduate School, Monterey, California, during the period August 1959 through May 1960. I am indebted to Professor S. H. Kalmbach for his guidance, assistance and patience as a faculty advisor; and to Professor A. Cooper for his valuable assistance.

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1. Introduction.

Infrared is an electromagnetic radiation generated by molecular thermal action within an object. Thus any object whose temperature is above absolute zero, generates infrared energy whose frequency ranges from approximately one million to 500 million megacycles.

All the infrared energy from a source impinging on a receiver is not detected. The receiver being the colder body becomes heated because, due to its lower temperature it radiates less heat than it receives from the source which is at a higher temperature. The receiver reflects some of the incident energy and absorbs the rest. Part of the absorbed energy is re-radiated by the receiver, part is removed by convection and part by conduction. The best one could hope to detect as there are no perfect absorbers, is the incident energy minus the reflected portion minus the energy reradiated.

A black body represents a limiting case never quite reached by an actual body. A black body absorbs all thermal radiation striking it and is also a perfect radiator. All other bodies are called grey bodies. The Stefan-Boltzmann law states that the amount of radiation from a black body is proportional to the fourth power of the absolute temperature.[1]

$$W_t = A_s \sigma \left(T_s^4 - T_o^4 \right)$$

where: A_s is the area of the source.

σ is the Stefan-Boltzmann constant.

T_s is the absolute temperature of the source.

T_o is the absolute temperature of the surroundings.

[1] V.M. Faires, Applied Thermodynamics, pp. 437 - 439. The Macmillan Company, 1950.

The infrared energy radiated by an object is not monochromatic. The energy spreads over a wide wavelength range and is distributed nonuniformly throughout this range going through a maximum value at some wavelength λ_m. λ_m is determined by the objects temperature and for a black body is equal to one micron when the blackbody temperature is 2897 ^{o}K.[2] This is known as the Wien Displacement Law ie: as the temperature of an object increases, the peak radiation shifts to shorter wave lengths.

$$\lambda_m = \frac{2897}{T}$$

Where T = the absolute temperature of the black body.

Atmospheric absorbtion limits the transmission of infrared energy to well defined wavelengths with the greatest window between eight and 13 microns which is the far infrared (FIR) region of the infrared region of the spectrum. For military applications, FIR generally refers only to the above window. This investigation will be primarily concerned with the eight to thirteen micron window.

Thermal detectors are generally passive detection systems in that they do not transmit a signal to be bounced off a target as radar systems do. For this reason a thermal detector cannot give range directly. When several detectors are utilized for triangulation, the range may be determined but the accuracy falls off with increasing range. However, passive systems are difficult to jam and make less strict demands than active systems regarding weight, space requirements, power needs, complexity and maintenance. For these reasons an intensive effort is being made to de-

[2] Smith, Jones and Chasmer, The Detection and Measurement of Infra-Red Radiation, p. 309, Oxford 1957.

valor a for passive infrared detector.[3]

Infrared detectors presently in use are primarily of the bolometer, photoconductor and the Mecourie types.[4] The bolometer is a blackened ribbon of metal which absorbs incoming radiation and changes it to heat. The rise in temperatrue affects the electrical resistance and the variation is used as a measure of incident radiation. The thermistor bolometer utilizes a semiconductor that is not photosensitive. A large drop in resistance is caused by the incident radiation. The thermistor bolometer has a wide band response but is not as sensitive as the photosensitive semiconductor detectors called photoconductors. The bolometer is capable of operating in the far but lacks the desired sensitivity. Photoconductors are used in the near and intermediate regions of the infrared spectrum. The incident energy absorbed by the photosensitive semiconductive material changes the conductivity of the semiconductor and the change in conductivity is used as a measure of the amount of radiation absorbed by the detector. Some photoconductive materials being used are lead sulfide, lead telluride, lead selenide and germanium. The photoconductors increase their sensitivity and wavelength response when they are cooled but also suffer an increase in their time constant which is undesireable. The necessity for cell cooling should be avoided whenever possible for military applications but without cooling it seems unlikely that photoconduct-

[3] Fundamentals of Infrared for Military Applications (U), U.S. Air Force Project Rand, pp. 1-52, R-297 (Confidential), March 1, 1956.

[4] F.J. Mass, IR System Designer Faces Many Hurdles, Aviation Week, March 11, 1957.

ors will ever be useful in the FIR region. Research is still being conducted in the hope of finding a photosensitive semiconductive material that will yield a sensitive detector in the FIR region. At present writing, no such material has been found.

The thermocouple consists of a pair of thermoelectric junctions with one junction blackened to receive the incident radiation. The normal system of detection utilizes the thermocouple as a source of voltage to be amplified and then measured. The thermocouple covers a wider band of the infrared spectrum than the photoconductor cells but requires considerably more incident energy for optimum performance, ie; is less sensitive than the photoconductor cell but does operate in the FIR region. If some means could be found for improving the sensitivity of the thermocouple, the need for a detector that is capable of detecting objects a few degrees above ambient temperature would be satisfied. At the present time there are no detectors in the FIR region with the sensitivity of the ones developed for use in the near and intermediate infrared regions.

The detector constructed for this thesis utilizes a short circuited thermocouple to generate a magnetic field near the path of an electron beam. The deflection of the electron beam results in a measurable current at the indicator which indicates the presence of an infrared signal.

The purpose of this investigation is to construct and determine the feasibility and limitations of such an infrared detector in the FIR region.

2. The Infrared Detector.

The infrared detector (Fig.1) consists of a low velocity electron gun, a thermocouple and wire loop, a long electron beam tube and a deflection indicator. These will be discussed separately in subsequent sections.

Since the sensitivity of the detector depends on its ability to indicate small deflections of the electron beam, it is important that the beam maintain its integrity during its passage down the beam tube. To prevent distortion of the beam it was necessary to construct a vacuum system enclosing the wire loop, electron gun and indicator in order to decrease the mean free path (ℓ) of the electrons . (At a pressure of 3.5×10^{-5} mm of mecury $\ell \cong$ 150cm and at a pressure of 10^{-6} mm of mercury $\ell \cong$ 65 meters.) Since the measured distance between the electron gun and the indicator was 77.5 centimeters, it became obvious that the vacuum would have to be 3.5×10^{-5} mm of mercury or better in order to achieve satisfactory results.

The necessity of maintaining a vacuum of the above order of magnitude complicated the construction of the components as soft solder could not be used for electrical connections and all leads had to be through uranium glass seals in order to ensure a good air tight bond of glass to metal. The use of emery cloth and acetone was found to be effective in removing the flux from the silver solder connections and once the technique of glass blowing was mastered the vacuum system was constructed.

In spite of the vacuum, some dispersion of the electron beam is to be expected. The finite size of the emitter and the force of repulsion between the electrons due to their like charges will tend

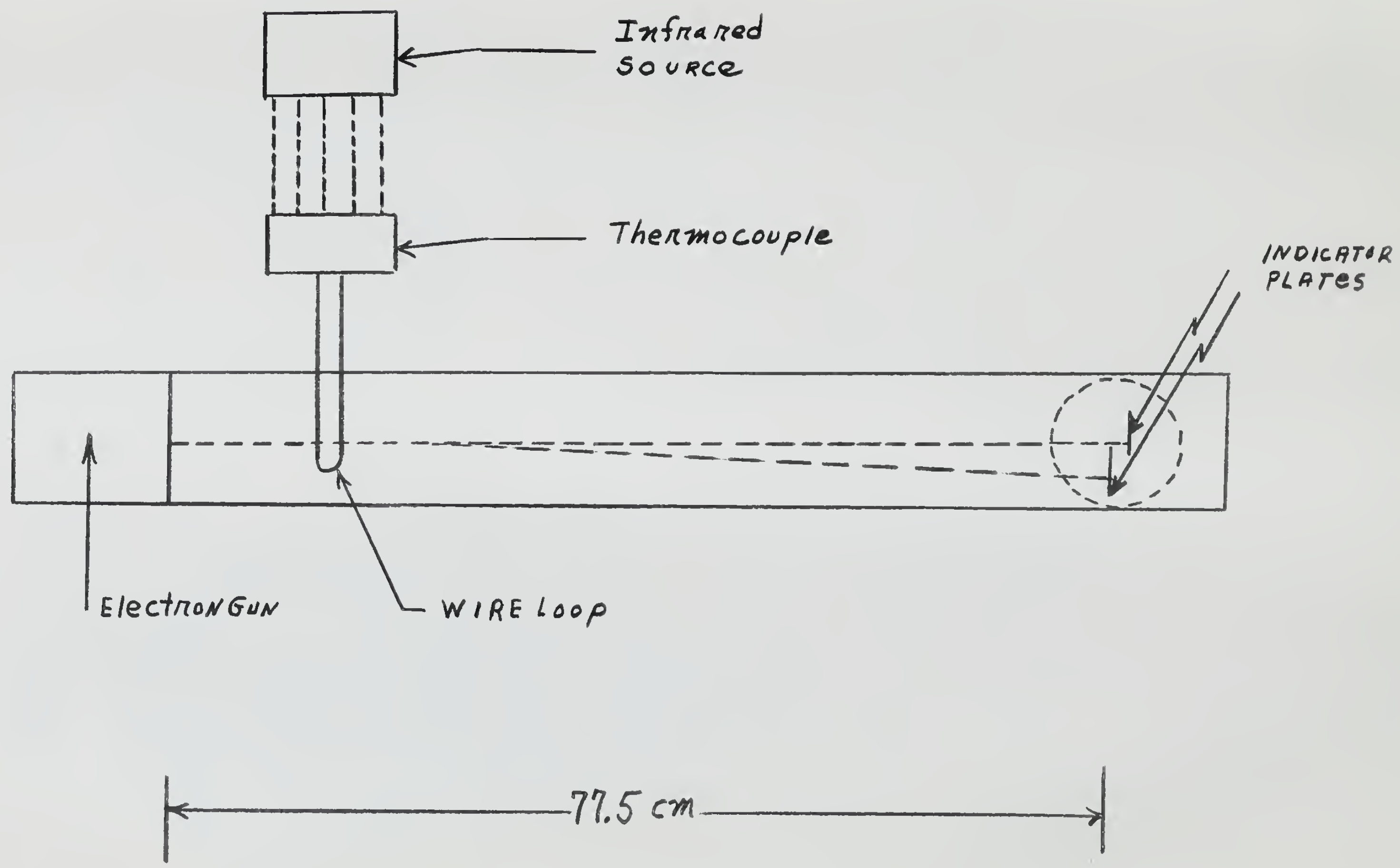
Infrared Source
Thermocouple
INDICATOR PLATES
ElectronGun
WIRE Loop
77.5 cm

fig 1

to cause the beam to spread as it travels down the tube. For this reason, an electron gun with a good focus and a small emitter surface was required.

3. The Indicator.

For indicating the deflection of the electron beam, two parallel copper plates were suspended through a ground glass joint. Each copper plate was silver soldered to a tungsten wire that passed through a uranium glass vacuum seal. By sealing the two wire lead pinch to one piece of the two piece ground glass joint, the attached copper plates could then be rotated inside the evacuated tube. The above suspension of the copper plates placed them approximately perpendicular to the electron beam and separated the plates, ie. no electrical path between the plates.

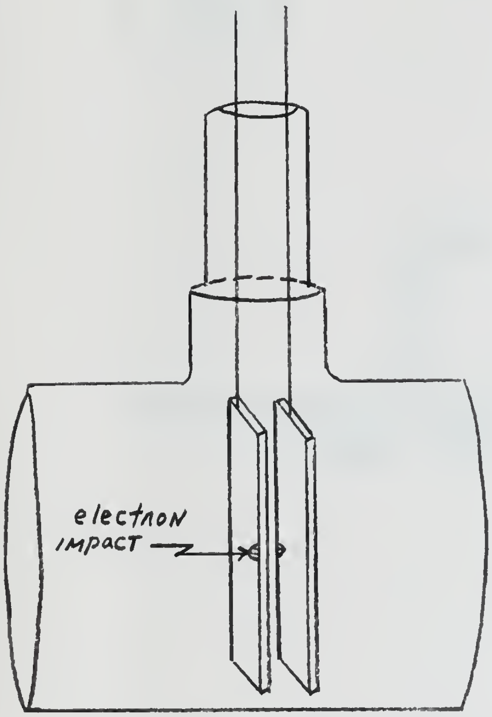

fig 2

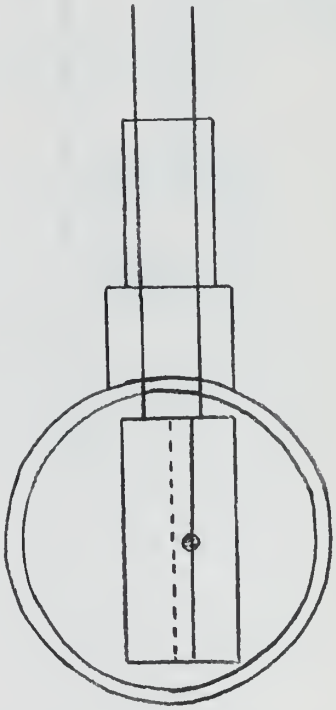

fig 3

With the electron gun turned on and the infrared source shielded from the thermocouple, the copper plates can be rotated until all of the electron beam is striking the grounded plate (See fig. 4 for electrical

circuit). Then by use of a large wire coil placed in front of the plates outside the tube, the electron beam is adjusted onto the knife edge formed by the overlapping copper plates. The plate connected to the galvanometer through the aryton shunt then will have an increment of the beam incident upon it with most of the electron beam on the grounded plate.

Electrical Circuit of Indicator

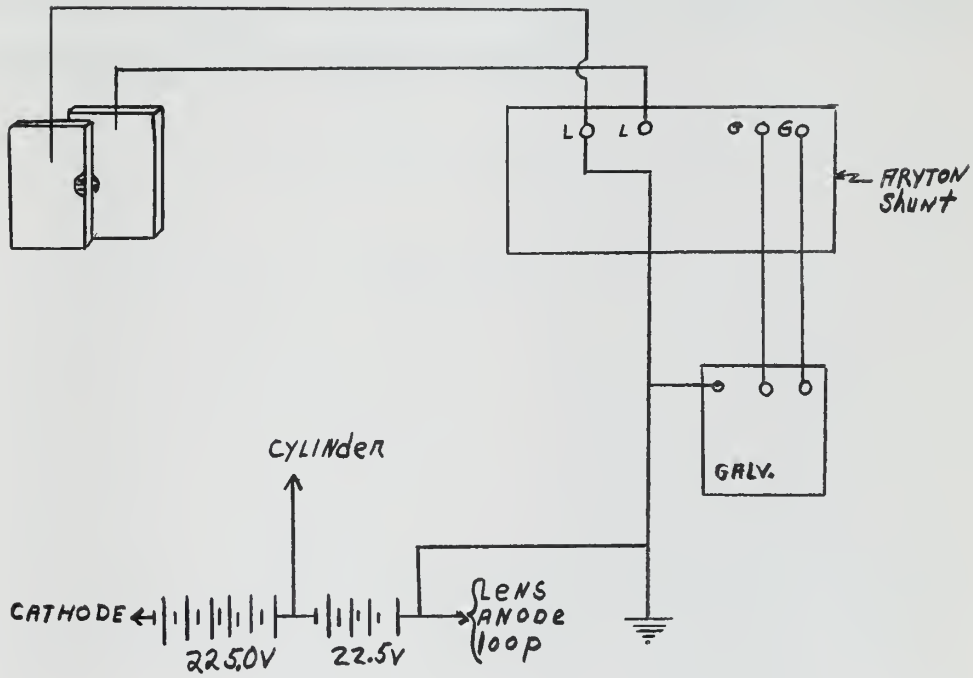

fig. 4

It is necessary to have an increment of the beam on the non grounded plate in order to insure that any deflection of the beam will result in a measurable current. If the plate does not have an increment of the electron beam, there is no way of knowing whether or not any deflection of the beam will result in a current as the beam may not be on the knife

edge. The deflection of the galvanometer caused by the increment of the electron beam can either be recorded as a reference current or effectively removed by rezeroing the galvanometer.

Once the knife edge adjustment of the beam and subsequent zeroing of the galvanometer have been made, the shielding between the thermocouple and infrared source may be removed and the deflection of the galvanometer recorded. In this manner, one is able to obtain a plot of black body temperature versus the current caused by the deflection of the electron beam and determine the minimum black body temperature above ambient that can be detected with this detector.

4. The Thermocouple.

The I R energy incident on the gold foil receiver of the thermocouple generates a voltage (emf) at the thermocouple junction. If the thermocouple circuit is short circuited, a current will flow in the circuit. The original idea was to construct a thermocouple loop of Bismuth and Bismuth Tin extruded wires of .0010 inch and .0013 inch diameters respectively. By mounting the thermocouple on a copper cylinder the thermocouple would be short circuited and the current would flow in the loop formed by the two wires and cylinder. The current in the loop generates a magnetic field near the loop and should cause a deflection of the electron beam by the following equation:[5]

$$\bar{F} = e\,(\,\bar{E} + \bar{V} \times \bar{B}\,).$$

Where: $\bar{F}$ = Force excerted on electron

e = Charge of electron

$\bar{E}$ = Electric Field

$\bar{B}$ = Magnetic Field

$\bar{V}$ = Velocity of electron

Since the deflection of the electron beam would be proportional to the magnetic field generated by the current, it was decided to construct the loop as small as possible in order to minimize the electrical resistance and thus generate a maximum magnetic field. Bismuth and its alloy of tin were selected because of their excellent junction thermoelectric power of 90 microvolts per degree centigrade.[6]

[5] L. Page, Introduction to Theoretical Physics, p.444, D. Van Nostrand Company, Inc; 1947.

[6] W. L. Boakes, An Investigation of Infrared Detection by Electronic Scanning of a Thermocouple, p.12, United States Naval Post Graduate School, 1958.

The Proposed Thermocouple

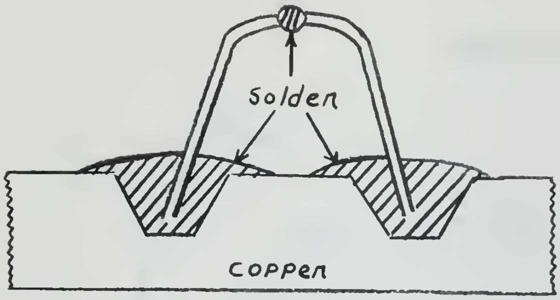

fig 5

Due to the small size of the thermocouple assembly, special handling tools had to be made, a micromanipulator and a miniature heater to melt the solder were constructed, and a double ocular microscope procured.

Since the melting point of woods metal is 73 °C and that of Bismuth 271 °C, woods metal was used as a solder and zinc chloride used as a flux. No difficulty was encountered in soldering the wires to the copper cylinder once the technique had been mastered but I was unable to solder the two wires together as the flux failed to wet the solder and the project had to be abandoned due to lack of time to pursue the problem further.

A thermocouple manufactured by Farrand Optical Co. Inc; Trademark FOC1, mounted in a sealed metal container with a crystal IR Transparent window was procured (see fig.6). The crystal window would absorb water if exposed to the atmosphere and so a container was manufactured to contain the thermocouple and dessicant. A glass tube was joined to

the forepump end of the vacuum system and connected to the thermocouple housing by means of a rubber stopper and glyptol in order to improve the thermocouple response time.

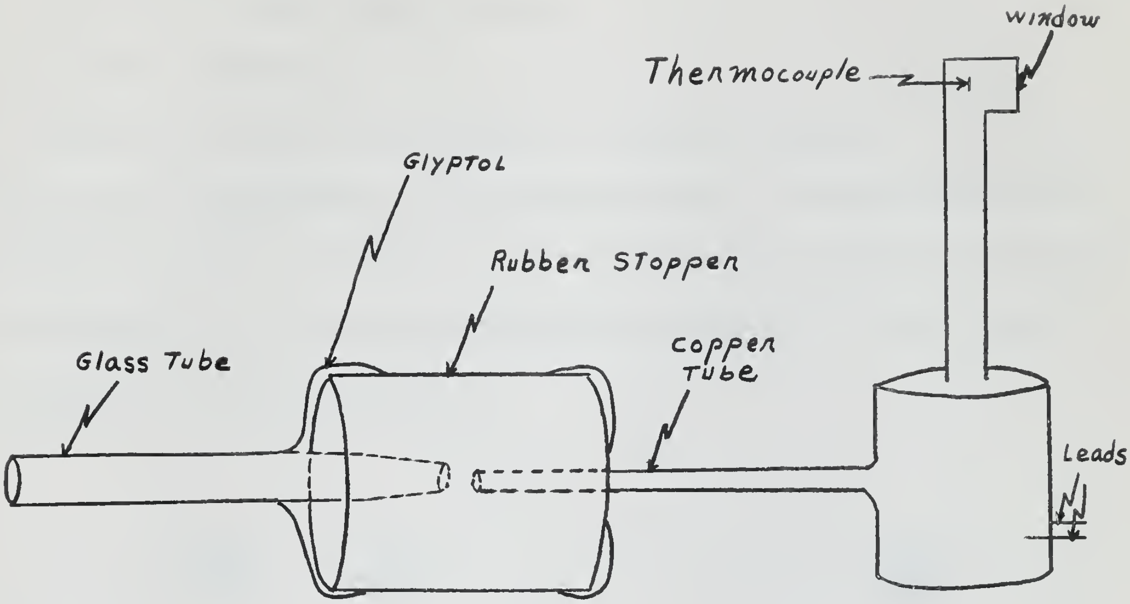

Fig 6

No specifications were available for the thermocouple and its operational status was unknown. Therefore, before utilizing the thermocouple to generate an emf and deflect the electron beam, the thermocouple had to be checked to determine if it was operational and what its parameters were.

To determine the area of the blackened gold foil receiver, the thermocouple was placed under a traveling microscope. The receiver was a square 7.5×10^{-4} meters on a side with an area (A_r) equal to 5.625×10^{-7} square meters.

For the calibration of the thermocouple, an IR source was requir- ed that would generate IR energy at a known temperature and emissive

area at a fixed distance from the thermocouple. (See section 5 for IR source). The emissive area (A_s) and the distance (D) separating the source and thermocouple were measured and found to be:

A_s = 2.01×10^{-4} square meters.

D = .041 meters.

With the IR source turned on at a constant temperature, the thermocouple may be considered to be a source of emf. By connecting the thermocouple to a known resistance in series with a galvanometer, the internal resistance (R_t) of the thermocouple and the emf or open circuit voltage (E_o) may be determined.

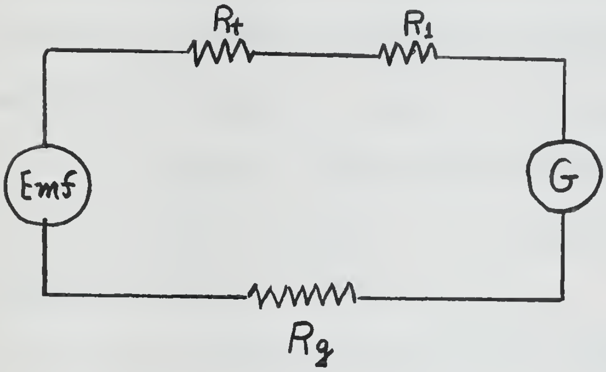

fig 7

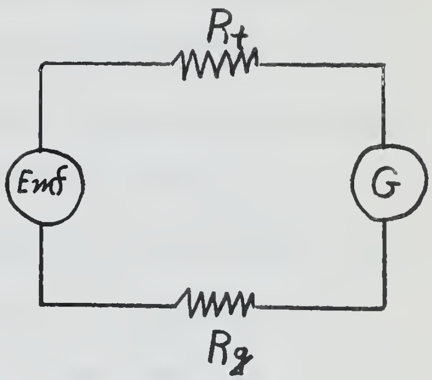

fig 8

Connecting the circuit as shown in figures 7 and 8 results in the following equations :

$$\text{emf} = I_1 \; (R_t + R_1 + R_g)$$

$$\text{emf} = I_2 \; (R_t + R_g) = E_o$$

solving simultaneously:

$$R_t = \frac{I_2 \; (R_g) - I_1 \; (R_1 + R_g)}{(I_1 - I_2)}$$

Where: R_g 24 ohms

R_1 24 ohms

Considerable difficulty was experienced with the galvanometer movement due to environmental noise. In an attempt to minimize the random fluctuations of the galvanometer, measurements were taken at night until 0400 hours with no noticeable decrease in the fluctuations.

Since the deflection of the galvanometer was only several orders of magnitude times the zero drift when the IR source was near ambient temperatures, it was decided to operate the IR source at temperatures greater than twice ambient temperatures in order to minimize the error in reading the galvanometer. The critical damping external resistance for the galvanometer of 430 ohms was felt to be more than the external resistance used. For this reason, the galvanometer was believed to be over damped. Since the period of the galvanometer when critically damped was 3.5 seconds, measurements were taken at ten second intervals. The data obtained appeared to be consistent until R_t was computed yielding values of one to 105 ohms for R_t. A plot of the period of the galvanometer indicated that readings should have been taken at intervals of 30 seconds.

An additional source of error was felt to be the shutter used between the thermocouple and IR source. The thin shutter of galvanized steel was replaced with a quarter inch slab of aluminum as it was felt that the thin shutter rose in temperature due to the IR source. The use of a heavy aluminum shutter of greater surface area enabled the shutter to remain at essentially a constant temperature. The shutter was operated by a pully and string manually and although not the optimum arrangement, consistent results were obtained.

Operating the IR source between $50^{\circ} - 65^{\circ}$ C, ambient temperature

at 23.5° C (T_o) the average internal resistance (R_t ave) was computed to be 13.0 ohms.

Computing E_o at: T_s 323° K

T_o 296.5° K

I_2 .1465 micro amps

yields: E_o 5.3×10^{-6} volts

Now that E_o has been obtained, it is possible to compute the responsivity (S_o) of the thermocouple. Responsivity is defined to be the ratio of the open circuit voltage (E_o) to the radient power incident on the receiver (W_d).

$$S_o = \frac{E_o}{W_d}$$

By the Stefan-Boltzmann Law, the energy transmitted (W_t) by a black body is:

$$W_t = A_s \sigma (T_s^4 - T_o^4) \cong 4 A_s \sigma (T_s^3) (T_s - T_o)$$

The energy received (W_r) is a function of the solid angle between the source and the receiver:

$$W_r = \frac{A_r A_s 4\sigma (T_s^3) (\Delta T)}{4 \pi D^2}$$

But the energy radiated from the IR source is subject to absorbtion by the atmosphere. The energy contained between eight and thirteen microns is approximately 29 percent of the total radiated at 300° K but atmospheric absorbtion reduces the detectable energy to about 20 percent.

Therefore: $W_d = 0.2 W_r$

and where: D = .041 meters

$A_r = 5.625 \times 10^{-7}$ square meters

$A_s = 2.01 \times 10^{-4}$ square meters

$\sigma = 5.669 \times 10^{-8}$ watt / square meter $°K^4$

$T_s = 323° K$

$T_o = 296.5° K$

Then $W_d = 21.85 \times 10^{-8}$ watts

And $S_o = 24.3 \dfrac{\text{volts}}{\text{watt}}$

5. The IR Source.

The IR source used for calibation of the thermocouple was the model R S - 1B/TC-1B from Barnes Engineering Company. This source is reputed to be very stable and capable of maintaing a constant radiating surface temperature unaffected by changes in ambient temperature, line voltage variations and transients, tube aging and replacement of individual components. The temperature desired was set by use of a dial on the control box and was direct reading.

The source consisted of a blackened aluminum conical cavity haveing a 14^{o} apex angle and surrounded by spaced heating elements to maintain a uniform temperature. The opening of the cavity was measured with a micrometer as being 0.629 inches in diameter yielding an area (A_S) equal to 2.01×10^{-4} square meters. The distance between the thermocouple and the opening was measured from the inside of the cavity as being 0.141 meters.

6. The Electron Gun.

A low velocity electron gun yielding electrons of approximately 100 electron volt energies in a narrow beam was desired. Unfortunately no such electron gun could be found and it was decided to use the electron gun from an oscilloscope tube instead. A Sylvania 5BP1 was obtained whose anode voltages were 2200 and 1,100 volts. It was hoped that by using much lower voltages the beam could still be focused and that the gun would be suitable. The 5BP1 had four deflection plates which could be utilized for deflecting the beam into the vicinity of the thermocouple wire loop.

The gun was extracted from the evacuated glass envelope by wrapping the glass in masking tape, placing in a cardboard box, and placing an oxygen torch flame onto the glass face to break the glass. The gun had to be removed from the glass envelope because the glass was not pyrex and could not be joined to a pyrex vacuum system even with a uranium glass seal.

A spacer was cut out of fiber glass material to separate the wires and position the gun inside the new glass envelope. The necessary fiberglass material was purchased at a boat store and a sample spacer coated with fiberglass placed in an existing vacuum system with no noticeable effect on the vacuum system down to 10^{-6} mm of mercury.

Defective vacuum gages (type VG-1A) were cut in half as each had four lead uranium glass wire seals and the electron gun required eight wire leads into the vacuum. The cut pinches were cleaned with acetone, copper wires silver soldered to the tungsten wires, porcelein insulating beads placed over the copper wires, and the pieces of glass joined together to form the necessary eight wire leads into the vacuum system. A simple task for an accomplished glass blower that required

a month of effort on my part until the technique was mastered.

The electron gun then was joined to the vacuum system and the vacuum turned on. Repairing the leaks and repairing the damage done by repairing the original leaks took a considerable amount of time measured in months but the vacuum was finally made leak proof and a pressure of 1.1×10^{-5} mm of mercury obtained with the electron gun heater at 6.3 volts. The power being supplied by two 6 volt Edison cells and variable resistors in series.

To determine if the cathode was emitting electrons, a milliampmeter was placed between the anode and cathode of the electron gun. The heater voltage was brought up to 6.3 volts and the potential between the cathode and anode varied between zero and 500 volts D.C. At no time was there an indication of current on the milliampmeter. It was decided that the cathode was not emitting electrons and another gun would be required.

An electron gun was obtained from Stewart and Company of Santa Cruz that produced a hollow beam of electrons focused by a nickel cylinder called the focusing lens. The gun was reputed to be capable of focusing the electron beam with an overall difference of potential between the cathode and lens of approximately 150 volts. As this would produce a low velocity beam of electrons, the gun was felt to be suitable except that no means were provided for deflecting the beamie; no deflection plates on the gun. It was felt howerer, that wire coils mounted externally to the vacuum system and near the gun would provide the deflection required (see section 7 and 8).

Due to thedifficulty encountered with making a glass envelope with wire leads for the first electron gun, it was decided to have

Mr. Dumas in Palo Alto, enclose the gun in glass. Mr Dumas agreed to do the glass blowing and a week later the gun was received in its glass envelope. Per agreement, the spacers were made of mica sheets drilled and cut to size and the glass envelope was enlarged at the open end to facilitate the joining of the gun to the old apparatus.

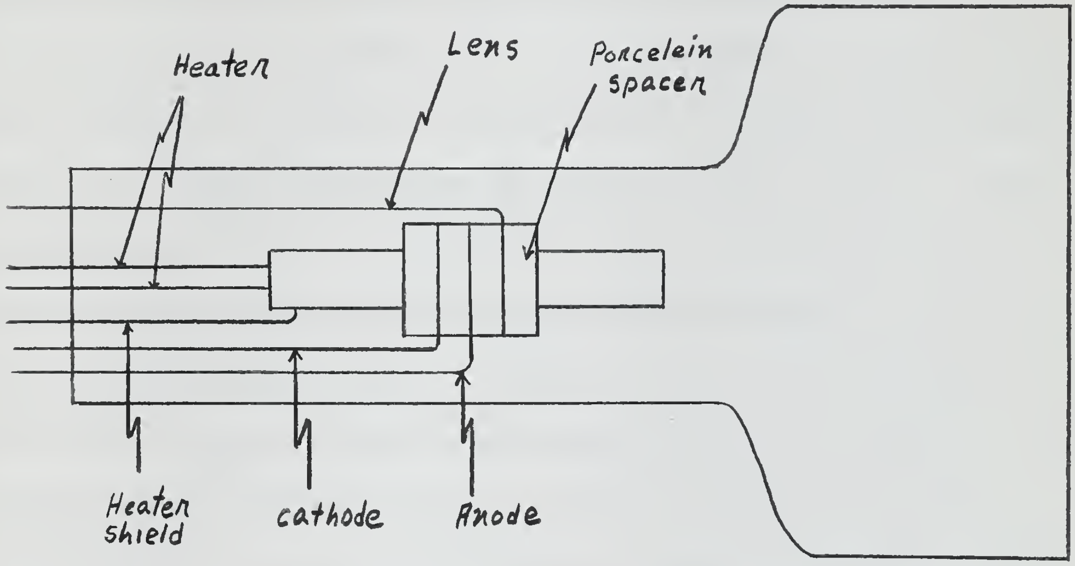

fig. 9

The first electron gun was removed from the vacuum system and the long beam tube washed out with acetone. The electron gun envelope was then connected to the tube. The air used for glass blowing was first passed through two liquid air traps to prevent moisture from contaminating the new apparatus.

The vacuum system was turned on and an induction heater used to heat up the electron gun. Hot air was passed over the vacuum system to remove any water vapor inside the system. After two days of bak-

ing out by this method, the pressure was down to 3.6×10^{-6} mm of mercury and the activation of the indirectly heated cathode was begun. It should be noted that the induction heater could not be used with the first electron gun because fiberglass spacers were used which would not stand the temperatures necessary to de-gas the metal components of the electron gun.

The conversion of the cathode is brought about by raising the temperature of the heater beyond the normal operating temperature. The heater operates at 6.3 volts after conversion and at a pressure equal to or less than 5×10^{-6} mm. The voltage on the heater was brought up slowly to 7.5 volts maintaining the pressure below 5×10^{-4} mm. When the pressure approached 5×10^{-4} mm the heater was turned off and the process repeated until the heater could be brought to 7.5 volts and have the pressure less than 5×10^{-6} mm. At this point the heater was left at 7.5 volts for twenty minutes then reduced to 6.3 volts. A milliampmeter was inserted between the anode and lens with a voltage of 90 volts between the anode and cathode and heater voltage at 6.3 volts to determine if the cathode had been converted. A current of 0.5 milliampers was read indicating that the cathode was emitting electrons and the activation of the cathode was successful. The conversion process was repeated later for 30 minutes with no increase in the indicated current so it was felt that the cathode was fully activated and no further conversion was attempted.

7. Focusing the Electron Beam.

The electrons emitted by the electron gun had to be focused into as small a beam as possible in order to achieve maximum intensity at the indicator plates 77.5 centimeters away. The focus lens and indicator were placed at the same potential relative to the anode. The anode was always kept positive with respect to the cathode. The heater, cathode and heater shield were connected externally and maintained at the same potential. Various combinations of potentials on the above components were then tried in an effort to obtain a deflection on the galvanometer connected to the indicator plates. No movement of the galvanometer was detected until the anode, lens and indicator plates were placed at the same potential of 270 volts positive with respect to the cathode. The reaction was almost immediate and violent in nature as all recording instruments went off scale. The current between the cathode and anode exceeded 1.5 milliampers, the galvanometer indicated a movement far in excess of 50 millimeters and the vacuum degenerated from 6.2×10^{-6} mm to 10^{-4} mm. The heater was turned off immediately, the scales on the instruments changed, and the procedure repeated several times. The readings on the instruments decreased with each succeeding run until finally the anode current was 0.41 ma, the galvanometer deflection was zero and the pressure was 1.8×10^{-6} mm.

In an effort to discover the cause for the decrease in the anode current it was noticed that one of the indicator plates now had a bright oval spot approximately half a centimeter in diameter located approximately a quarter of the way up from the bottom of the plates.

As the In source ceased operating prior to the above runs, it was repaired before anymore runs were made to ascertain the effect if any

on the galvanometer deflection.

The decrease in the anode current was felt to be due to the thermocouple wire loop projecting into the long beam tube as it had been left "floating". The loop was placed at the same potential as the anode, lens and indicator to prevent the building up of a negative charge around the loop.

The size of the shiny spot on the indicator plate led to the belief that better focusing was needed and a metal open ended cylinder was constructed to fit snugly around the glass tube just after the electron gun. It was hoped that application of a voltage to the cylinder would result in additional focusing of the beam.

The previous runs were repeated using various voltages on the cylinder with the following results. The deflections of the galvanometer were increased, the current between the cathode and anode decreased and remained constant for each run between 0.05 and 0.07 ma and the pressure rose to 3.8×10^{-5} mm. The wire coils were able to deflect the beam until a zero deflection was read on the galvanometer. However temperatures between $50^{\circ}C$ and $200^{\circ}C$ on the In source failed to deflect the beam. The optimum voltage for the metal cylinder was determined to be - 22.5 volts with respect to the anode. However the above deflections could only be detected when the pressure was at 3.8×10^{-5} mm which exceeded the recommended operating pressure for the heater. The problem of operating the gun at higher than recommended pressures was solved however by the abrupt termination of deflections on the galvanometer, the simultaneous drop in pressure to 3×10^{-6} mm and rise in anode current.

Subsequent runs only gave a brief deflection of the galvanometer when the heater was first turned on. A maximum deflection of 1.5mm was only obtained near previous settings of potentials (see fig. 10) for

electrical circuit). The wire coils were capable of returning this deflection to zero again.

Reversing the battery leads reversed the direction of the magnetic field and thus reversed the direction of the force on the electrons. This resulted in an opposite movement on the galvanometer. When too much force was being applied, the beam moved off the plate entirely. (The magnetic field excerted by the coils is experimentally determined in section 8.) From zero to 2.8 amps were placed upon the coils with no increase in the deflection on the galvanometer. The conclusion drawn from the above is that the beam of electrons never was focused or that the beam was brought to a focus too soon and then diverged making it impossible to increase the intensity of the electrons at the indicator.

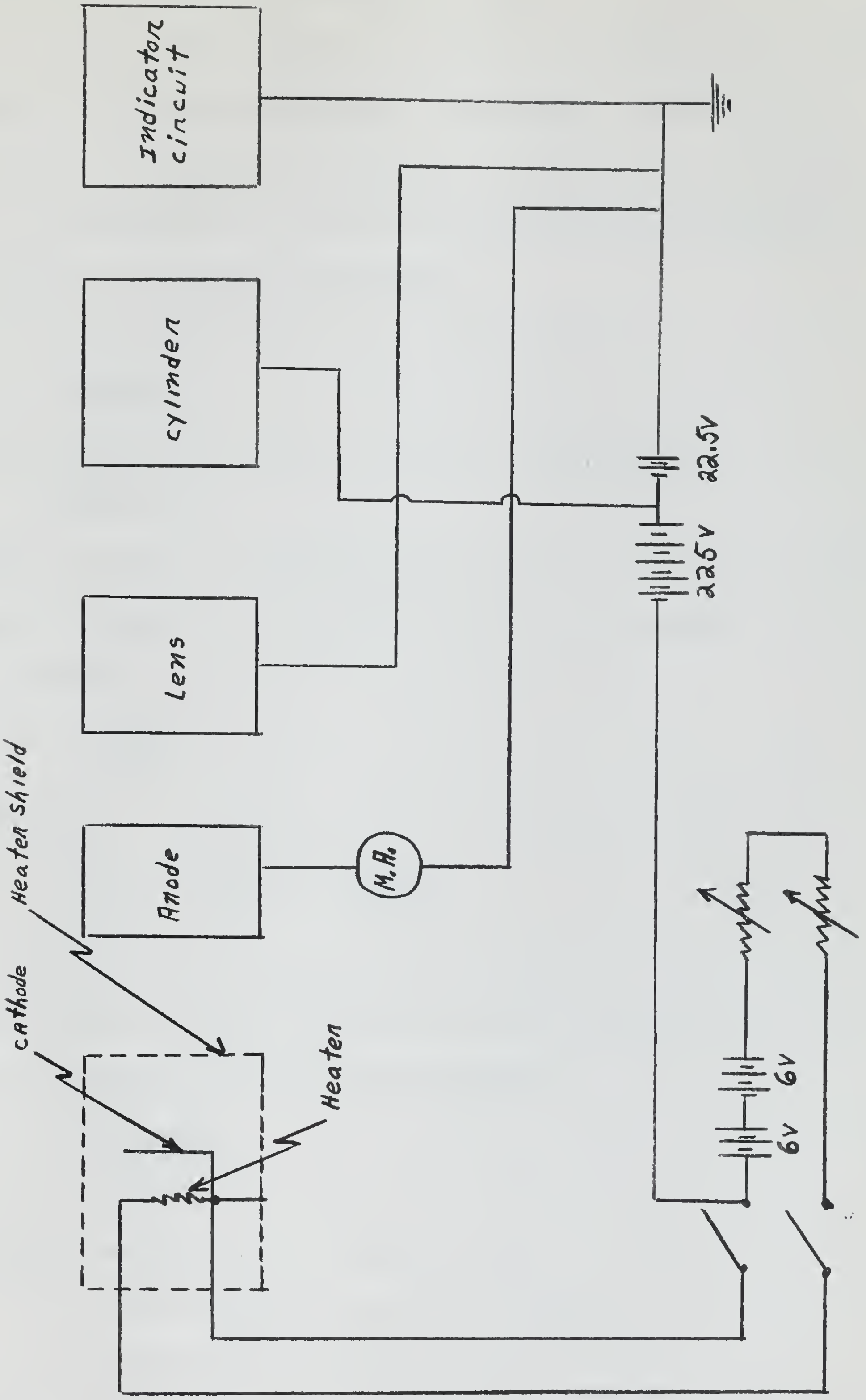
Indicator circuit
cylinder
Lens
Anode
M.A.
Heater Shield
cathode
Heater
22.5v
225v
6v
6v

fig. 10

8. Magnetic Deflection of the Electron Beam.

In order to determine the capabilities of the wire coils, the thermocouple wire loop and the proposed thermocouple (Section 4, fig. 5) in deflecting an electron beam, the magnetic field the electrons passed through was determined for the wire coils and computed by analogy for the wire loop and the proposed thermocouple.

Since the force excerted on an electron is:

$$F = Bev$$

The impulse which equals the change in Momentum is:

$$\int F dt = Bevt$$

Then the change in momentum of the electron caused by the force, divided by the mass of the electron results in the change of velocity of the electron, ie;

$$\Delta v = \frac{Bevt}{m}$$

The angle of deflection of the electron beam is then:

$$\theta = \tan^{-1} \frac{\Delta v}{v} = \tan^{-1} \left(\frac{Bet}{m} \right)$$

The magnetic field, generated by a current in a coil of wire at a distance equal to half the radius of the coil from the center of the coil can be computed by the following formula:

$$B_c = \frac{3.2 \pi N I}{\sqrt{5} \ a}$$

Where: N = the number of turns of wire

I = the current in the wire in ampers

a = the mean radius of the coil in meters

However, the average magnetic field (B_a) that acts on the beam of electronsis not equal to B_c because the field intensity will decrease

with distance from the coil. In order to determine B_a, a very small coil of wire with twisted leads to a galvanometer was placed parallel and opposite the center of the large wire coil and at a distance a/2 (5.71cm) from the coil. By moving the large coil to positions along a line parallel to the small coil, the current induced in the small coil can be measured on the galvanometer.

Since the current in the small coil is proportional to the magnetic field of the large coil, when the small coil is at the center position where B_c is known, the current (I_c) has a one to one correspondence with B_c and other values of the current can be scaled to this reference value.

By plotting the current or deflection on the galvanometer versus the parallel distance (r) between the centers of the large and small coils and graphically determining the area under the curve (A_u), the average magnetic field (B_a) between any two values of r may be determined.

$$B_a = \frac{A_u B_c}{A_t}$$

Where: A_t = the area contained in the rectangle I_c

The experiment as described was performed and the plot of galvanometer deflection versus distance obtained. (fig.11) The same distribution of magnetic field strength with distance will be obtained for different currents and number of turns. Since the ordinate of the curve is proportional to B_c and the length to the radius of the coil, the curve can be scaled to fit different size coils.

It should noted that figure 11 is only half of the curve and that the electrons would have a force exerted on them over a distance of

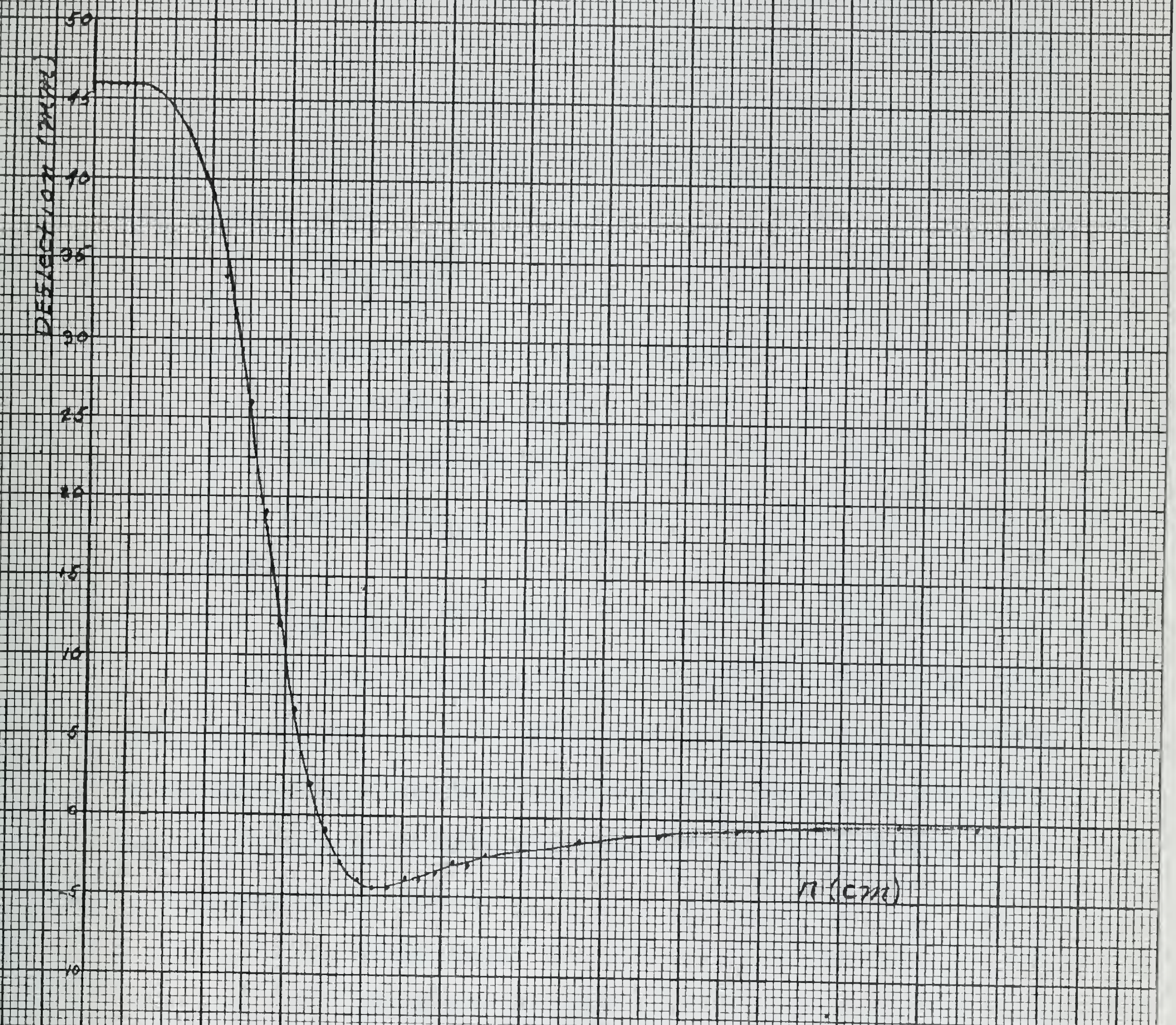

fig. 12

twice that shown on figurell. Neglecting that portion of the area between 45 and 75 cm, as it is small in comparison with the area between zero and 45, the effective length of the magnetic field is 90 centimeters or 7.87 times the radius of the coil. This scaling factor will be used later to compute the deflection of the electron beam by the thermocouple wire loop and the proposed thermocouple loop.

Since the time the electrons are exposed to the force generated by B_a is inversely proportional to the electron velocity, the velocity of the electrons caused by an accelerating potential of 247.5 volts must be determined.

$$v = \left(\frac{2ev}{m}\right)^{1/2}$$

Where: $v =$ the velocity of the electrons

$e =$ the electron charge

$V =$ the accelerating potential

$m =$ the mass of the electron

yields:

$$v = 9.3 \times 10^{-8} \text{ cm/sec}$$

The area under the curve in figure 11 was divided into two portions, ie; from zero to 15 cm and from 15 to 45 cm. Since the magnetic fielddistribution is twice figure 11, this resulted in four areas and four increments of deflection over a 90 cm path (see fig. 12).

Solving for B_c where:

$N = 200$ turns

$I = 28$ milliamperes

$a = 0.1145$ meters

Yields:

$$B_c = 0.219 \text{ gauss}$$

Substitution of the values for B and v into previous formulas, yielded the results tabulated in Table 1 for the large coil.

r_1 to r_2	-45 cm to -15 cm +15 cm to +45 cm	-15 cm to zero cm zero cm to +15 cm
A_u (Squares)	235	1921
A_t (Squares)	5520	2760
B_a (Gauss)	.0665	.1525
Δv ($\times 10^8$ cm/sec)	.0343	.40
TAN θ	.00322	.043
θ	0 11	2 28

Table 1.

The total deflection was then obtained over a 90 cm path by computing the deflection caused by the -45 to - 15cm incremental area, then since this deflection is opposite to that caused by the -15 to zero cm area it must be subtracted from the deflection caused by the later area, etc; a graphical sketch of the process is shown in figure 12 (not drawn to scale due to the size of the angles involved). The deflection over 90 cm with 28 milliamperes in the large coil is then:

$$\delta = 4.12 \text{ cm}$$

Since from zero to 2.8 amperes were in the coil (see section 7),

some deflection of the beam should have been indicated on the indicator if the electron beam were focused.

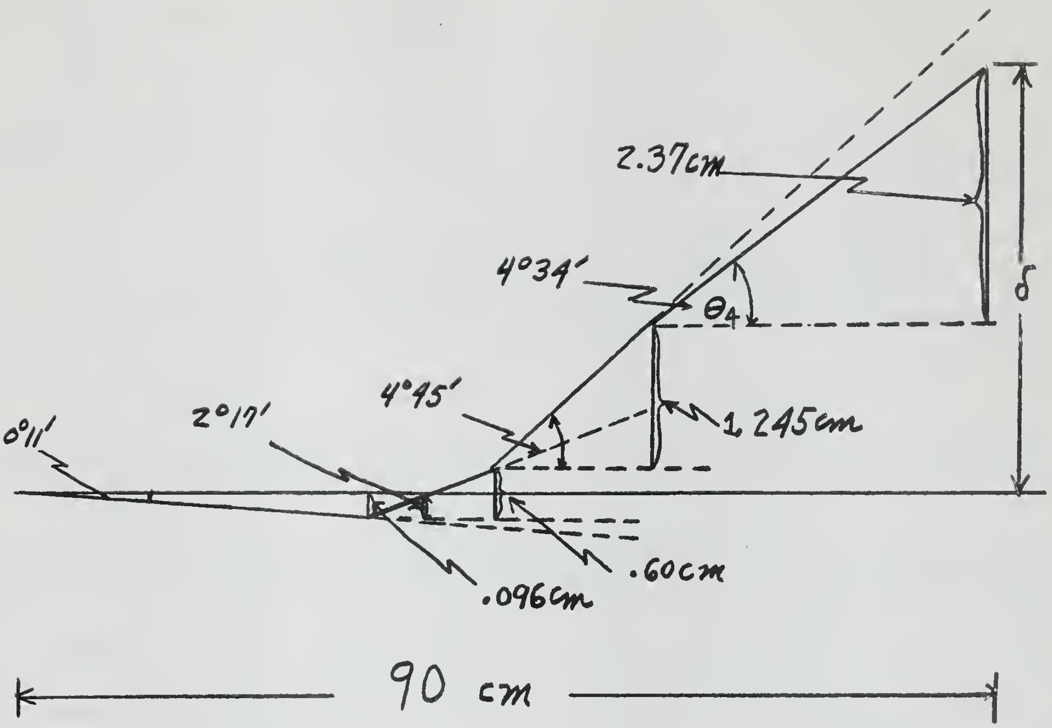

fig.12

The deflection of the electrons by the thermocouple and wire loop can be computed in a like manner. Since the emf of the thermocouple at 323° K was computed to be 5.3×10^{-6} volts (E) and the resistance of the wire loop and thermocouple was 13.1 ohms then solving for B_c :

Where:

$N = $ one

$a = .005$ meters

$I = 4.05 \times 10^{-7}$ amperes

Yields:

$B_c = 3.64 \times 10^{-7}$ gauss

In order to determine B_a, the scaling factor of 7.87 is multiplied

by the radius of the loop. Thus the magnetic field is effective over 3.93 centimeters instead of 90 cm as with the large coil. Proceeding in the same manner as before, the deflection over 3.93 cm is computed to be (see table 2 and fig. 13).

$$\delta = 1.31 \times 10^{-8} \text{ cm}$$

r to r	-1.968 to -.656cm + .656 to 1.968 cm	-.656 to zero cm zero to .656 cm
B_a (Gauss)	$.155 \times 10^{-7}$	2.62×10^{-7}
v cm/sec	.358	3.03
tan 0	$.384 \times 10^{-9}$	$.326 \times 10^{-8}$
0	2.21×10^{-8} degrees	18.8×10^{-8} degrees

Table 2

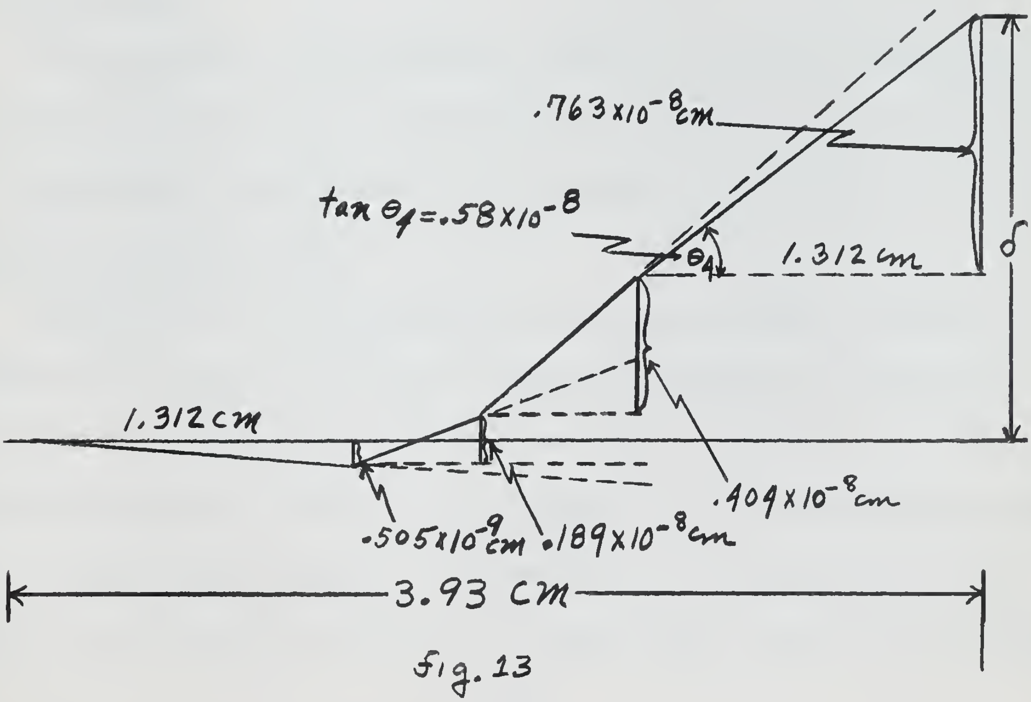

fig. 13

The deflection of the electron beam between the loop and the indicator will be greater than 1.27×10^{-8} cm however, because the loop and indicator are separated by 41.5 cm.

Therefore:

$$\delta_t = \delta + (41.5 - 3.92/2) \tan \theta_4$$

Where:

$$\delta = 1.31 \times 10^{-8} \text{ cm}$$

$$\tan \theta_4 = 0.58 \times 10^{-8}$$

$\delta_t =$ total deflection of beam by the wire loop

Yields:

$$\delta_t = 24.2 \times 10^{-8} \text{cm} = 2.42 \times 10^{-3} \text{ microns}$$

The deflection of the electron beam by the wire loop as computed above is very small and if the deflection is to be detected at the indicator, the beam of electrons must be very well focused or the change in intensity on the indicator plates will be too small to be detected by the galvanometer. Since the beam of electrons could not be focused, it now becomes apparent why the loop failed to indicate a deflection on the galvanometer.

The deflection of the electron beam by the proposed thermocouple loop must be computed on a theoretical basis alone since the thermocouple could not be constructed and the parameters could could not be determined experimentally.

Assuming that the thermocouple loop is constructed such that the radius of the wires is 10 microns, the loop diameter 60 microns, and that the IR source is at 300° K with an ambient temperature of 299° K, then from page 26 of Boakes (see footnote 6) the thermocouple current is 500 micro amperes (μa). The theoretical determination of this value involved some 20 pages by LT. Boakes andis accepted by the author

as a reasonable value.

Proceeding in the same manner as before and solving for B_c:

Where:

$N =$ one

$a = 30 \times 10^{-6}$ meters

$I = 500\ \mu a$

Yields:

$B_c = 7.4 \times 10^{-2}$ Gauss

Solving for the deflection over the scaled path length of 2.36×10^{-2} cm (see table 3 and fig. 14):

$$\delta = .918 \times 10^{-7} \text{ cm}$$

The total deflection between the thermocouple loop and the indicator is then:

$$\delta_t = \delta + (41.5 - .0236/2) \tan \theta_4 = 2.72 \text{ microns}$$

r_1 to r_2	$-.0117$ to $-.0039$ cm $+.0039$ to $+.0117$ cm	$-.0039$ to zero cm zero to $+.0039$ cm
B_a (Gauss)	.00315	.0532
Δv (cm/sec)	432	3,640
Tan ($\times 10^{-5}$)	.0465	.391
θ ($\times 10^{-5}$)	2.68°	22.4°

Table 3

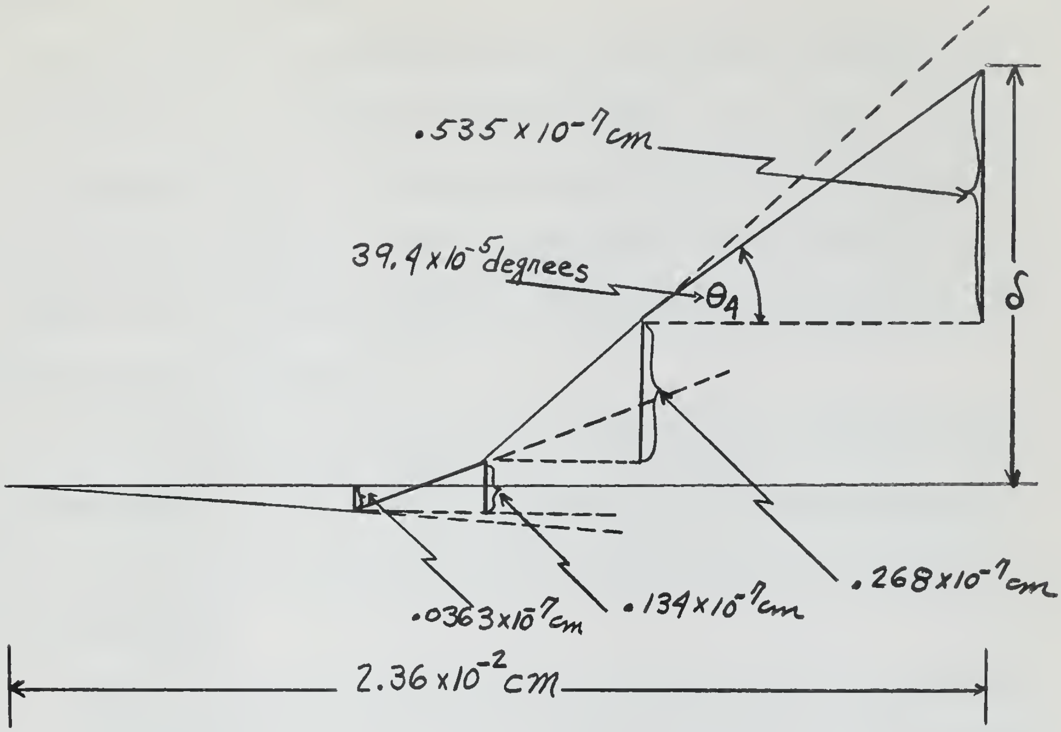
.535 x 10^-7 cm
39.4 x 10^-5 degrees
θ_A
δ
.0363 x 10^-7 cm
.134 x 10^-7 cm
.268 x 10^-7 cm
2.36 x 10^-2 cm

fig 14

9. Summary and Conclusions:

The IR detector was constructed and experimental determinations of the thermocouple and magnetic field parameters were made. The failure of the electron gun to focus the electron beam precluded the final experimental determination of the feasibility of the IR detector.

However the following conclusions can be made concerning the IR detector and its components:

a. The thermocouple used was less sensitive to IR than the proposed thermocouple as the measured current in the thermocouple used was much less than the current calculated by Lt. Boakes for the proposed thermocouple.

b. The wire loop and an external thermocouple left much to be desired as the proposed thermocouple mounted internally yielded a much larger calculated deflection of the electron beam.

c. The design of the indicator was successful as it was capable of experimentally measuring .00034 μa of incident electron intensity and this should be sensitive enough to be used as an indicator of electron beam deflection.

d. The vacuum system constructed was capable of providing the mean free path required for the electron beam to reach the indicator.

e. With the use of a better designed electron gun to provide good focusing of the electron beam and use of the proposed thermocouple, the IR detector should be feasible.

10. Recommendations.

Since the final experimental determination of the IR detector feasibility depends on the use of a better thermocouple and electron gun, it is recommended that they be constructed and used in the system.

Unfortunately the author has no recommended solution to the thermocouple flux problem and this will have to be left as a problem to be solved before the proposed thermocouple can be constructed.

However, an electron gun design has been located which has been used successfully to produce a collimated low velocity beam of electrons.[7]

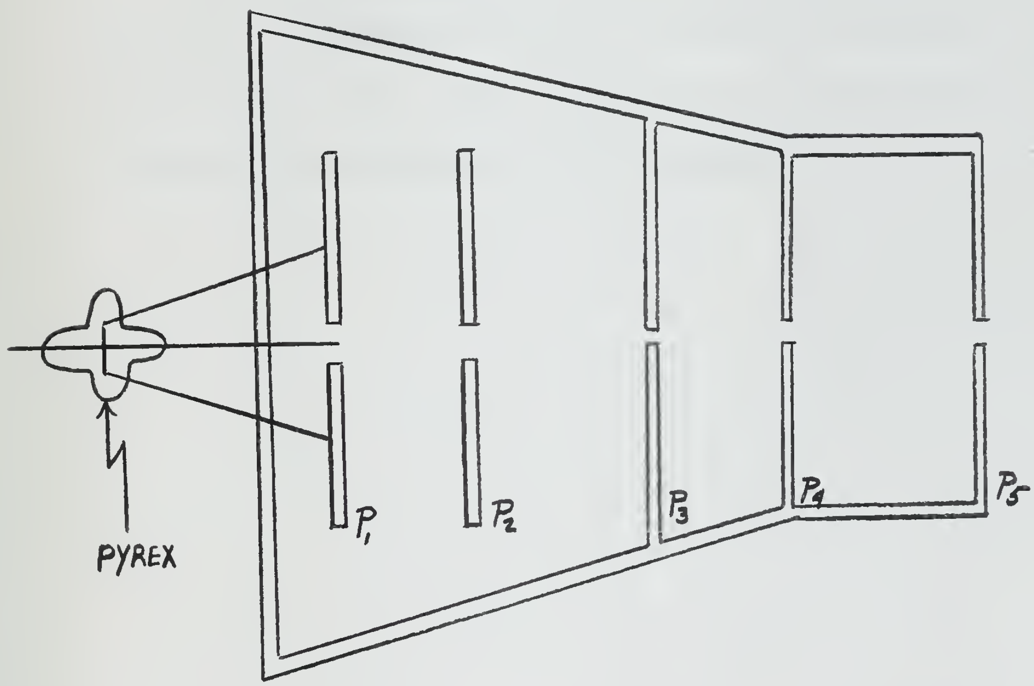

fig. 15

[7] Davidson and Germer, The Defraction of Electrons by a Crystal of Nickel, Physical Review, Vol 30, No 6, p. 705 December 1927.

The electron gun consists of a tungsten filament located in front of five aperatures to collimate the electron beam. Note that there is no indirectly heated cathode to be converted. The tungsten filament F lies in a rectangular opening in a nickel plate P_1. The purpose of this plate is to assist in concentrating the emission from the filament onto the opening in plate P_2. The potential of plate P_1 is more negative than that of the filament and the potential of P_2 is adjusted to a rather high positive value. Plates P_3 , P_4, P_5, are maintained at the same potential as the wall of the electron gun. The difference in the potential between the last three plates and the filament determines the speed of the emergent beam.

The gun as described was tested by Davidson and Germer and found to give a homogeneous beam with accelerating potentials between 54 and 248 volts. For this reason, it is recommended that this gun be constructed and utilized in the IR detector.

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